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(71) Applicant: MASSACHUSETTS INSTITUTE OF  
TECHNOLOGY [US/US]; 77 Massachusetts Avenue,  
Cambridge, MA 02139 (US).

(72) Inventors: JOANNOPOULOS, John, D.; 64 Douglas  
Road, Belmont, MA 02478 (US). KOLODZIEJSKI,  
Leslie, A.; 56 Carleton Road, Belmont, MA 02478 (US).  
FAN, Shanhui; 50 Porter Street, Apt. 2, Somerville, MA

02143 (US). PETRICH, Gale, S.; 215 Massachusetts Ave.,  
Apt. 33, Arlington, MA 02474 (US). VILLENEUVE,  
Pierre, R.; 61 Brookline Avenue, Apt. #407, Boston, MA  
02215 (US).

(74) Agents: CONNORS, Matthew, E. et al.; Samuels,  
Gauthier & Stevens, LLP, Suite 3300, 225 Franklin Street,  
Boston, MA 02110 (US).

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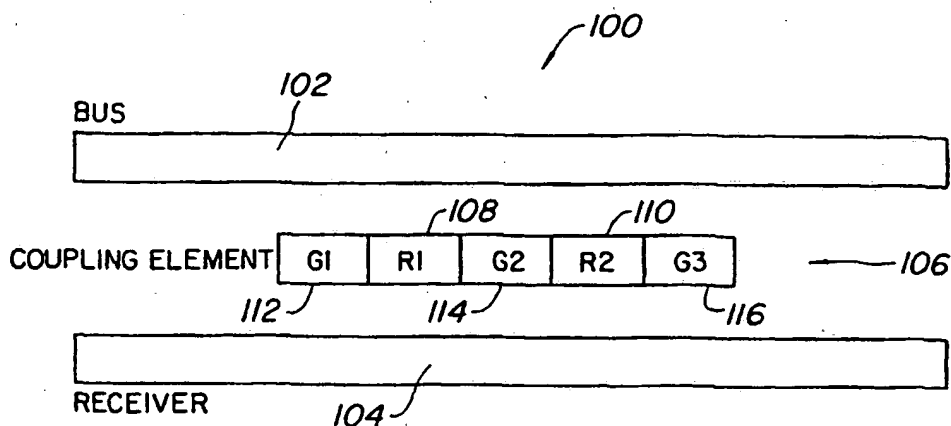
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(54) Title: TUNABLE ADD/DROP FILTER USING SIDE-COUPLED RESONANT TUNNELING



(57) Abstract: A tunable electromagnetic field frequency filter (100) having an input waveguide (102) which carries a signal including at least one desired frequency, and an output waveguide (104). A resonator-system is coupled to the input and output waveguides and is operable for the selective transfer of the at least one desired frequency to the output waveguide. The resonator-system supports at least two system modes, and includes at least three reflectors (G1, G2, G3) with at least two different reflectivity spectra. Two resonators (R1, R2) are defined by the three reflectors (G1, G2, G3). At least one of the reflectivity spectra is tuned such that at least two of the system-modes have substantially the same frequency when the transfer occurs substantially.

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## TUNABLE ADD/DROP FILTER USING SIDE-COUPLED RESONANT TUNNELING

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### PRIORITY INFORMATION

This application claims priority from provisional application Ser. No. 60/162,177 filed October 28, 1999.

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### BACKGROUND OF THE INVENTION

The invention relates to the field of tunable add/drop filters using side-coupled resonant tunneling.

Add/drop filters play a vital role in wavelength division multiplexed (WDM) lightwave communications systems. They allow different wavelengths to be added or removed from an optical transmission line. Add/drop filters come in one of two classes: static or dynamic. Static devices are designed to operate at a given fixed wavelength predetermined during the fabrication process. Dynamic devices are designed to be switched on and off to add or remove selected wavelengths from a transmission line and, in some cases, are also designed to be tunable, i.e., single devices can be made to add or remove any one of a number of different wavelengths.

Examples of dynamic filters include acousto-optic tunable filters (AOTFs), polymer-based thermo-optic switches, and micro electromechanical systems (MEMS). These filters suffer from a variety of physical limitations such as high crosstalk, frequency insensitivity, and overall large size. This latter feature makes some of the filters unsuitable for very large scale integration (VLSI). In fact, a single AOTF can be as large as one square inch.

Recently, an optical switch based on side-coupled resonant tunneling suitable for VLSI has been designed and described in U.S. Pat. No. 6,101,300 entitled "HIGH EFFICIENCY CHANNEL DROP FILTER WITH ABSORPTION", of common assignee. The switch is activated by changing the internal decaying rate of a resonant coupling element located between two adjacent waveguides. While being very small in size, the switch was designed mostly to add or drop a specific wavelength, determined during fabrication, with limited post-fabrication tunability, i.e., the user could select the wavelength to be added or dropped within only a small range.

### SUMMARY OF THE INVENTION

In accordance with the invention, there is provided a tunable add/drop filter capable of selectively adding or dropping one or more wavelength over a wide range of wavelengths.

The tuning range can be made large enough to cover the entire bandwidth of a WDM system. The specific wavelength can be selected after fabrication. Post-fabrication tunability over a wide range is a highly desirable feature. It allows, for example, devices to be adjusted during installation. Control signals are adjusted to select a wavelength and the device is left to operate continuously at the selected wavelength, or the device could be electronically and remotely driven to dynamically switch between different wavelengths (such as in optical add/drop multiplexers) allowing fast reconfigurability of optical networks.

The add/drop filter includes two waveguides coupled by an element containing at least two resonators. It is the coupling element that determines the transfer properties of the add/drop filter such as the wavelength of the transferred electromagnetic field. The wavelength of the coupling element in the invention is tunable over a wide range of wavelengths.

In accordance with one embodiment of the invention there is provided a tunable electromagnetic field frequency filter having an input waveguide which carries a signal including at least one desired frequency, and an output waveguide. A resonator-system is coupled to the input and output waveguides operable for the selective transfer of the at least one desired frequency to the output waveguide. The resonator-system supports at least two system modes, and includes at least three reflectors with at least two different reflectivity spectra. At least one of the reflectivity spectra is tuned such that at least two of the system-modes have substantially the same frequency when the transfer occurs substantially.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a tunable add/drop filter in accordance with the invention;

FIGs. 2A-2C are schematic graphs of the reflectivity spectra of the three gratings shown in FIG. 1;

FIG. 3 is a plan view of a first exemplary embodiment of the invention;

FIG. 4 is a plan view of a second exemplary embodiment of the invention;

FIG. 5 is a cross sectional view of the waveguide shown in FIG. 4 along the dashed line 5-5 in which the device is tuned using the electro-optic effect;

FIG. 6 is a cross sectional view of the waveguide shown in FIG. 4 along the dashed line 5-5 in which the device is tuned using the injection of charge carriers; and

FIG. 7 is a cross sectional view of the waveguide shown in FIG. 4 along the dashed line 5-5 in which the device is tuned using the thermo-optic effect.

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### DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 is a schematic diagram of a tunable add/drop filter 100 in accordance with the invention. The filter includes two waveguides that are labeled "bus" 102 and "receiver" 104. A coupling element 106 has a resonator system comprising two resonators, labeled R1 108 and R2 110. The resonators are defined using three gratings, labeled G1 112, G2 114, and G3 116. The reflectivity spectra of the gratings consist of combs of reflection peaks, i.e., series of discrete frequency regions of high reflectivity separated by regions of low reflectivity. Examples of gratings include, but are not limited to, sampled gratings, chirped gratings, and super-structure gratings. Some examples are shown in the following two references: "Tunable Laser Diodes" by M.-C. Amann and J. Buus, published by Artech, Boston (1998); and "Design of Widely Tunable Semiconductor Lasers and Concept of Binary Superimposed Gratings (BSG's)" by I. Avrutsky, D. Ellis, A. Tager, H. Anis and J. Xu, published in IEEE J. Quant. Elect., vol. 34, no. 4, pp. 729-741 (1998), both of which are incorporated herein by reference.

20 The two resonators are coupled through grating G2 and are further coupled through the waveguides. Each resonator supports at least one mode and the resonator system supports at least two system modes. The system modes are eigenmodes of the resonator system formed in part by a linear combination of the resonator modes. Substantial transfer occurs between the bus and the receiver when the two system modes have substantially the same resonant frequency and the same overall decay rate. However, the invention does not necessarily have a plane of symmetry perpendicular to the waveguides. The wavelength of the transferred signal is selected by changing the resonant frequency of the resonators. This is accomplished by changing the reflectivity spectrum of the gratings and by adjusting the round-trip path length inside the resonators to insure resonance. The reflectivity and the round-trip path length can be adjusted, for example, using a variety of physical phenomena such as carrier injection, thermal heating, or the electro-optic effect.

The comb-like reflectivity spectra of the three gratings are shown schematically in the graphs of FIGs. 2A-2C. Each spectrum consists of a series of reflection peaks separated

by a different frequency spacing  $\Delta f_i$  ( $i=1, 2$ , or  $3$ ). The features of the reflectivity spectra depend on the physical parameters of the gratings; each grating has a different set of physical parameters. Since each grating has a different frequency spacing, it is possible to align one reflection peak from each grating, i.e., all three gratings have a reflection peak at the same frequency, while keeping all other reflection peaks misaligned. Tuning is accomplished by frequency shifting at least one of the reflection spectra.

Only small frequency shifts are needed to misalign the reflectivity peaks. Moreover, other peaks can be made to coincide resulting in the resonators being resonant at a different frequency. This effect, called the Vernier effect, is used to tune the filter over a wide frequency range while using only small frequency shifts. It is used in certain tunable laser sources for WDM applications. See, for example, "Widely tunable 1.55- $\mu\text{m}$  lasers for wavelength-division-multiplexed optical fiber communications", F. Delorme, IEEE J. Quant. Electron., Vol. 34, pp.1706-1716 (1998), incorporated herein by reference.

The coupling of the two resonators through G2 (the "direct" coupling) causes frequency splitting of the two system modes. This direct coupling is compensated by "indirect" coupling through the waveguides. The indirect coupling depends on the optical path length between the resonators which in turn depends on the frequency of the resonant modes. In order to guarantee cancellation of direct and indirect coupling for any frequency, it is necessary to adjust the phase of the signal in the waveguides. This can be accomplished, for example, using the electro-optic effect.

FIG. 3 is a plan view of an exemplary embodiment of a tunable add/drop filter 300 of the invention. The filter includes two waveguides that are labeled bus 302 and receiver 304. The filter includes a coupling element 306 having a resonator system comprising two resonators, labeled R1 and R2. The resonators are defined using three gratings, labeled G1, G2, and G3. In this embodiment, the waveguides (both the bus and the receiver) are curved to minimize the transfer of non-resonant channels occurring through waveguide coupling, and back reflection from the gratings. The cross-hatched regions correspond to metal electrodes 308, 310 located above the waveguides, and metal electrodes 312, 314, 316, 318, 320 located above the resonators and gratings, respectively. In this exemplary embodiment, a voltage is applied to each electrode to change the optical properties of the materials. There are six control signals:

$S_{G1}$ ,  $S_{G2}$ , and  $S_{G3}$  are used to shift the reflectivity spectra of G1, G2, and G3, respectively, hence are used to select (tune) the desired channel;

- $S_{\phi 1}$  and  $S_{\phi 2}$  are used to satisfy the round-trip resonant condition in each resonator; and
- $S_{ind}$  is used to satisfy the cancellation of direct and indirect coupling between the resonators.

5 Alternatively, the filter could be operated by shifting only two reflectivity spectra, leaving the third unaffected. One reflectivity spectrum could be aligned with the standard International Telecommunication Union (ITU) grid, though this is not necessary to meet ITU standards. Also,  $S_{ind}$  could be driven with two separate sources.

In the exemplary embodiment shown in FIG. 3, each resonator has a single resonant  
10 mode within the frequency range  $\delta f_i$ , where  $\delta f_i$  is defined as the width of the reflection peaks of grating  $i$ . The optical resonant modes extend spatially in (and beyond) the resonators over a total length  $L$ .  $L$  is the *effective* length of the resonators and is different than the physical length of the resonator. The frequency spacing  $Df$  between two adjacent resonant frequencies is given by:

$$15 \quad Df = c/(Ln_{eff})$$

where  $n_{eff}$  is the effective index of refraction of the materials in the resonator region. The product  $Ln_{eff}$  is defined as the optical length of the resonators. Since the resonators support only one resonant mode within the frequency range  $\delta f_i$ ,  $\delta f_i$  must be smaller than  $Df$ . This sets an upper limit on the effective length of the resonators:

$$20 \quad L < c/(2n_{eff}\delta f_i)$$

In the specific case where  $n_{eff} = 3$  and  $\delta f_1 = \delta f_2 = \delta f_3 = 10\text{GHz}$ , the effective length of the resonator must be less than 5mm.

The frequency spacing  $\Delta f_i$  of the different reflection peaks is given by:

$$\Delta f_i = c/(2l_i n_{eff,i})$$

25 where  $l_i$  is the length of the repeating unit of grating  $i$ ,  $n_{eff,i}$  is the effective index of grating  $i$ , and  $l_i n_{eff,i}$  defines the optical length of the  $i$ -th reflector. In the specific case where  $n_{eff,2} = 3$  and  $\Delta f_2 = 100\text{GHz}$ , the length of the repeating unit of grating 2 is 500 $\mu\text{m}$ . The frequency spacing can be modified by changing the length of the grating.

In another embodiment, the width of the reflection peaks is made larger such that it  
30 overlaps with more than one frequency channel. In this embodiment, multiple channels are transferred between the two waveguides simultaneously.

FIG. 4 is a plan view of another exemplary embodiment of a tunable add/drop filter  
400. The filter includes two waveguides that are labeled bus 402 and receiver 404. The filter includes a coupling element 406 having a resonator system comprising four resonators,

labeled R1-R4. The resonators are defined using six gratings, labeled G1-G6. In this embodiment, the waveguides (both the bus and the receiver) are curved to minimize the transfer of non-resonant channels occurring through waveguide coupling, and back reflection from the gratings. The cross-hatched regions correspond to metal electrodes 408, 410 located above the waveguides, and metal electrodes 412, 414, 416, 418, 420 located above the resonators and gratings, respectively. In this exemplary embodiment, a voltage is applied to each electrode to change the optical properties of the materials.

As in the previous embodiment there is a total of seven metal electrodes. While the use of two resonators in the previous embodiment resulted in a Lorentzian-shaped transfer function, the presence of four resonators in the current embodiment results in a non-Lorentzian transfer lineshape. The use of four resonators has the advantage of generating "flat top" and "sharp sidewall" response characteristics. Additional resonator pairs could be added to this embodiment to further modify the transfer lineshape.

The tunable add/drop filter presented in this disclosure can be fabricated in any of a large number of material systems such as III-V or II-VI compound semiconductors, or Si-based material systems. FIG. 5 shows the cross section of an exemplary embodiment of a waveguide 500 as represented along dashed line 5-5 of FIG. 4. FIG. 5 shows an InGaAsP ridge waveguide 502 buried in an InP substrate 504, with a backside metal contact 506. However, it will be appreciated by those skilled in the art that other waveguide geometries and other material systems can also be used. A metal electrode 508 is deposited on top of an insulating layer 510. FIG. 5 illustrates a configuration for adjusting the device using the electro-optic effect.

FIG. 6 is a cross section of another exemplary embodiment of a waveguide 600 taken along dashed line 5-5 of FIG. 4. FIG. 6 illustrates a configuration for tuning the device using the injection of charge carriers. Waveguide 600 includes an InGaAsP waveguide 602 buried in an InP substrate 604, with a backside metal contact 606. In this embodiment, an uppermost insulating layer is omitted and optional current-confinement layers 608 are added to help confine the carriers in the area of the waveguide. Furthermore, in this specific embodiment, doped semiconductors are used to promote current injection. A metal electrode 610 is deposited on the surface.

In yet another embodiment, the device is tuned using the thermo-optic effect. FIG. 7 is a cross section of an exemplary embodiment of a waveguide 700 taken along dashed line 5-5 of FIG. 4. A waveguide 702 of doped  $\text{SiO}_2$  is buried in a layer 704 of undoped  $\text{SiO}_2$ , which is provided on a Si substrate 706. In this embodiment, resistive metal heaters 708 are used to locally change the material temperature, hence the index of refraction. Although the

thermal effect is generally slower than the electroabsorption and electro-optic effects, i.e., the tuning speed is lower, the device retains its large range of tunability.

Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the  
5 form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is:



CLAIMS

- 1        1. A tunable electromagnetic field frequency filter comprising:  
2        an input waveguide which carries a signal having at least one frequency including at  
3        least one desired frequency;  
4        an output waveguide; and  
5        a resonator-system coupled to said input and output waveguides operable for the  
6        selective transfer of said at least one desired frequency to said output waveguide, said  
7        resonator-system supporting at least two system modes, said resonator-system comprising at  
8        least three reflectors with at least two different reflectivity spectra, at least one of said  
9        reflectivity spectra being tuned such that at least two of said system-modes have  
10       substantially the same frequency when said transfer occurs substantially.
- 1       2. The filter of claim 1, wherein said reflectivity spectra comprise regions of high  
2       reflectivity with narrow bandwidths.
- 1       3. The filter of claim 2, wherein said regions of high reflectivity are in close  
2       proximity to said desired signal frequency when said transfer occurs substantially.
- 1       4. The filter of claim 1, wherein said reflectors comprise periodic gratings.
- 1       5. The filter of claim 4, wherein said gratings have sampled periodicity, super-  
2       structure periodicity, modulated periodicity, or chirped periodicity.
- 1       6. The filter of claim 4, wherein said periodic gratings produce reflectivity spectra  
2       with regions of high reflectivity with narrow bandwidths.
- 1       7. The filter of claim 1, wherein said at least one reflectivity spectrum is tuned by  
2       changing the optical length of the reflector.
- 1       8. The filter of claim 7, wherein said optical length is changed by changing the  
2       refractive index or physical length of the reflector.
- 1       9. The filter of claim 7, wherein said optical length is changed by employing an

2 electric, optical, electro-optic or thermal effect.

1 10. The filter of claim 7, wherein said optical length is changed by injecting carriers  
2 or by applying an electric field.

1 11. The filter of claim 8, wherein said refractive index or physical length is changed  
2 by changing temperature.

1 12. The filter of claim 1, wherein said resonator-system comprises at least one pair  
2 of resonators that couple directly with said input waveguide and not directly with said output  
3 waveguide.

1 13. The filter of claim 1, wherein said resonator-system comprises at least one pair  
2 of resonators that couple directly with said output waveguide and not directly with said input  
3 waveguide.

1 14. The filter of claim 1, wherein said resonator-system comprises at least one pair  
2 of resonators that do not couple directly with either said input or output waveguides.

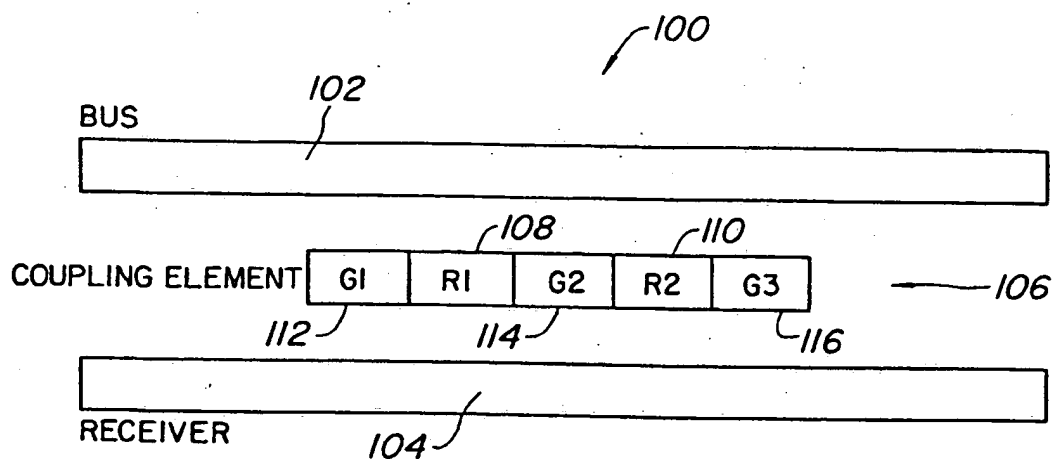
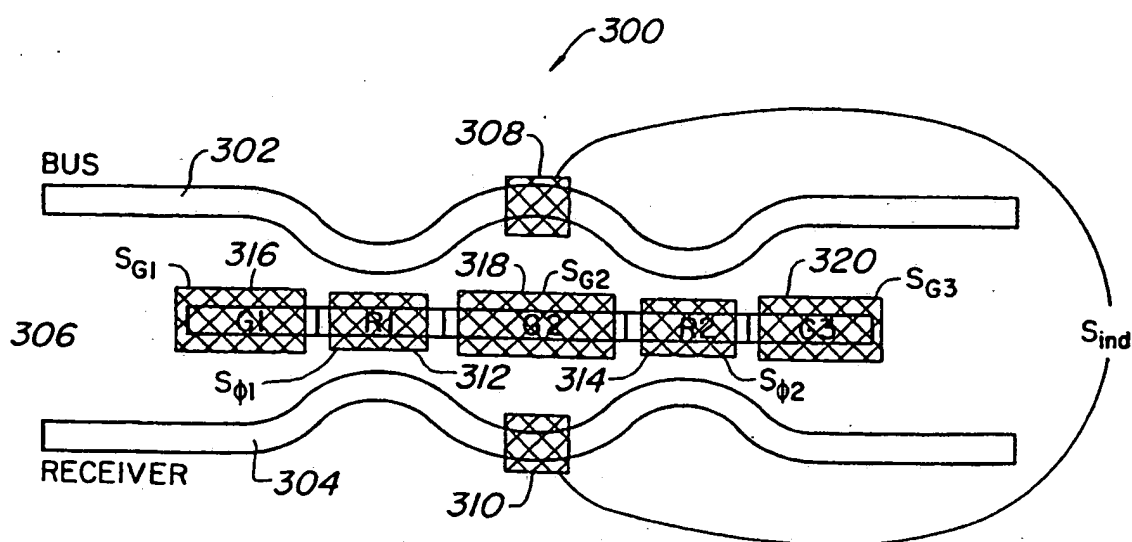
1 15. The filter of claim 2, wherein the optical length of the resonators are tuned such  
2 that the frequencies of said system modes lie within said regions of high reflectivity when  
3 said transfer occurs substantially.

1 16. A method of selectively transferring electromagnetic fields between two  
2 waveguides comprising:

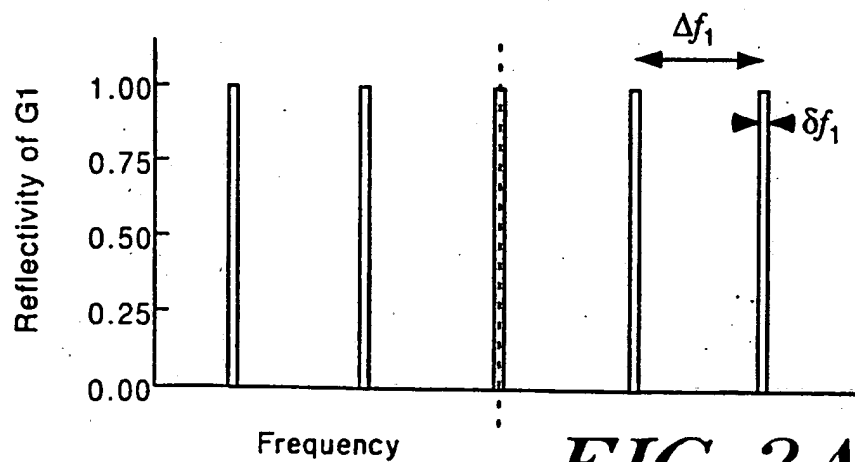
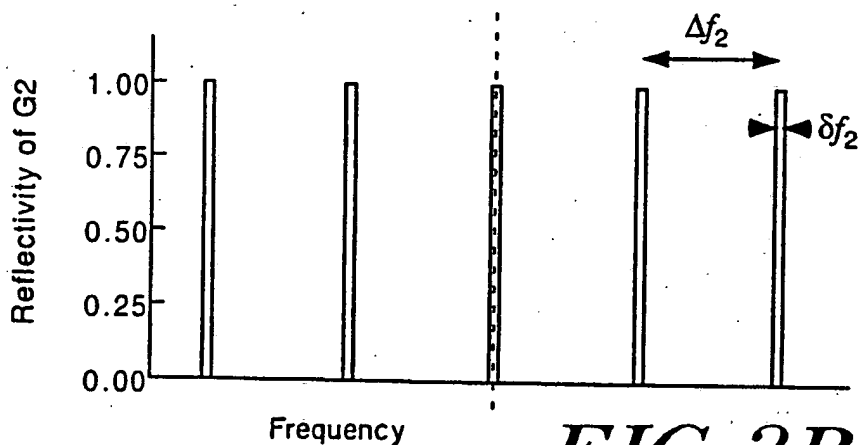
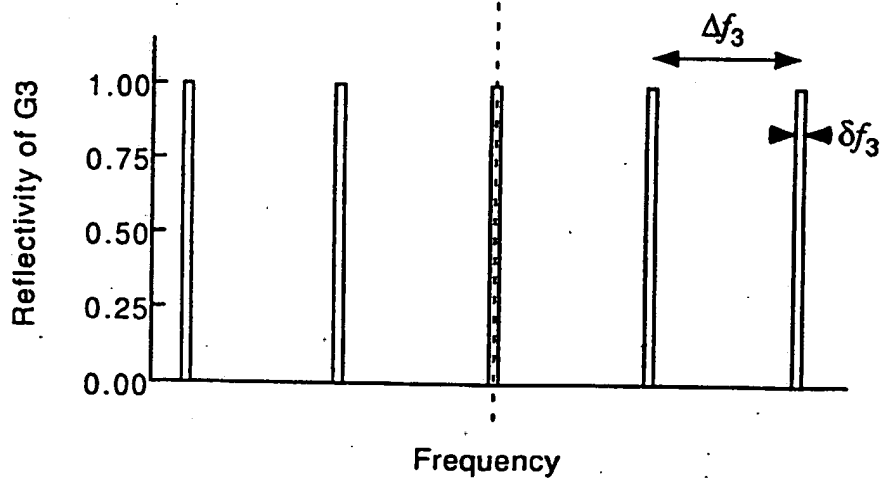
3 providing an input waveguide which carries a signal having at least one frequency  
4 including at least one desired frequency, and an output waveguide; and

5 coupling a resonator-system to said input and output waveguides, said resonator-  
6 system supporting at least two system modes, said resonator-system comprising at least  
7 three reflectors with at least two different reflectivity spectra, at least one of said reflectivity  
8 spectra being tuned such that at least two of said system-modes have substantially the same  
9 frequency when said transfer occurs substantially.

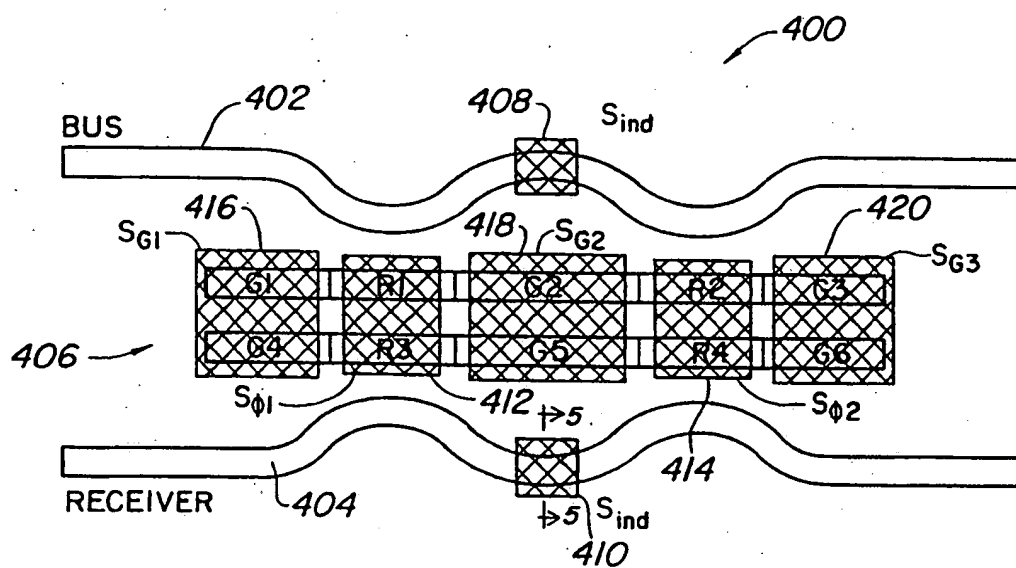
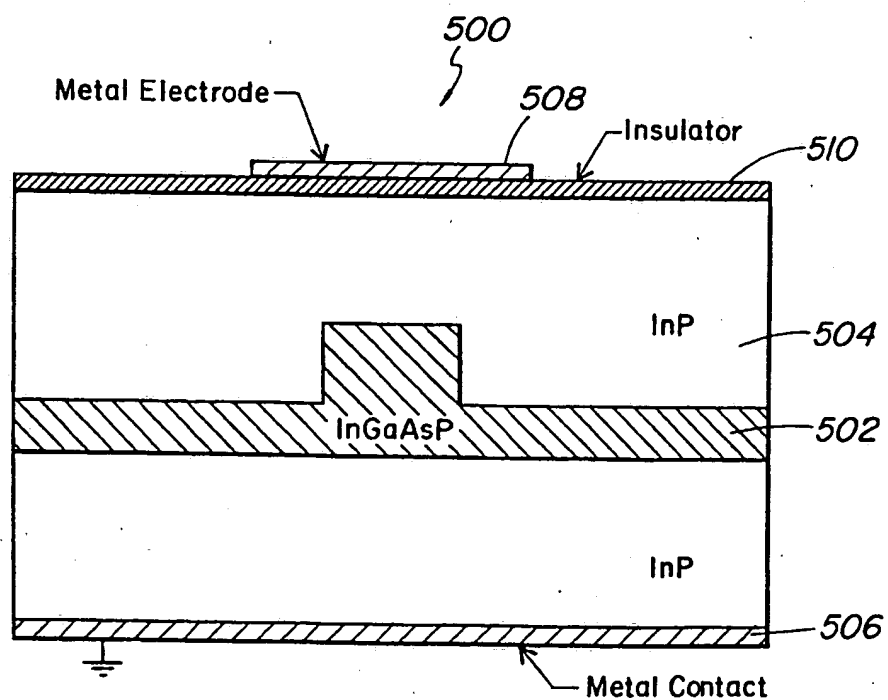
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*FIG. 1**FIG. 3*

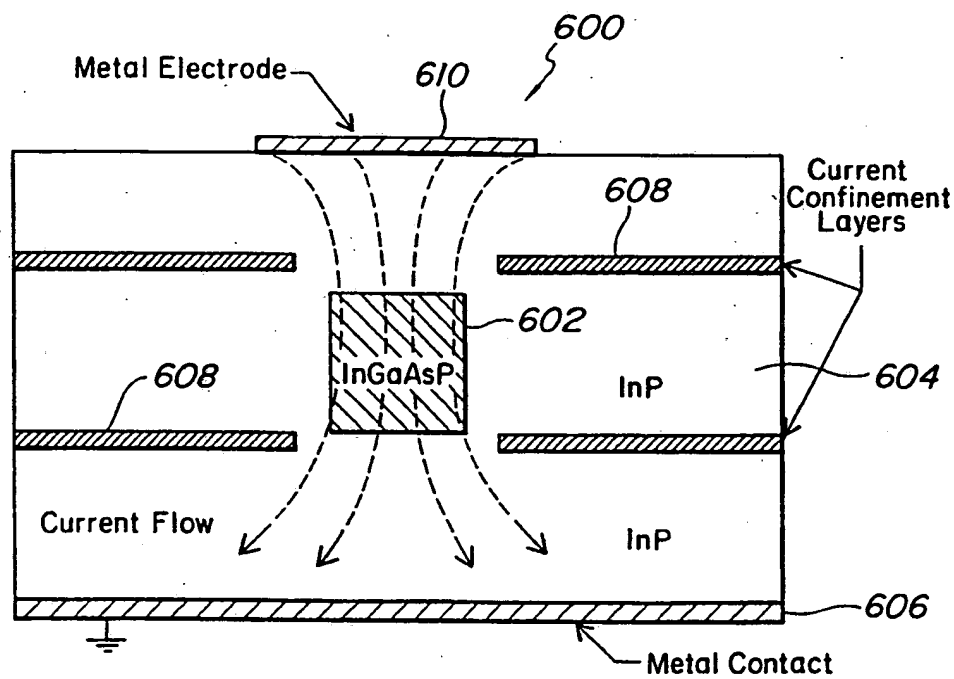
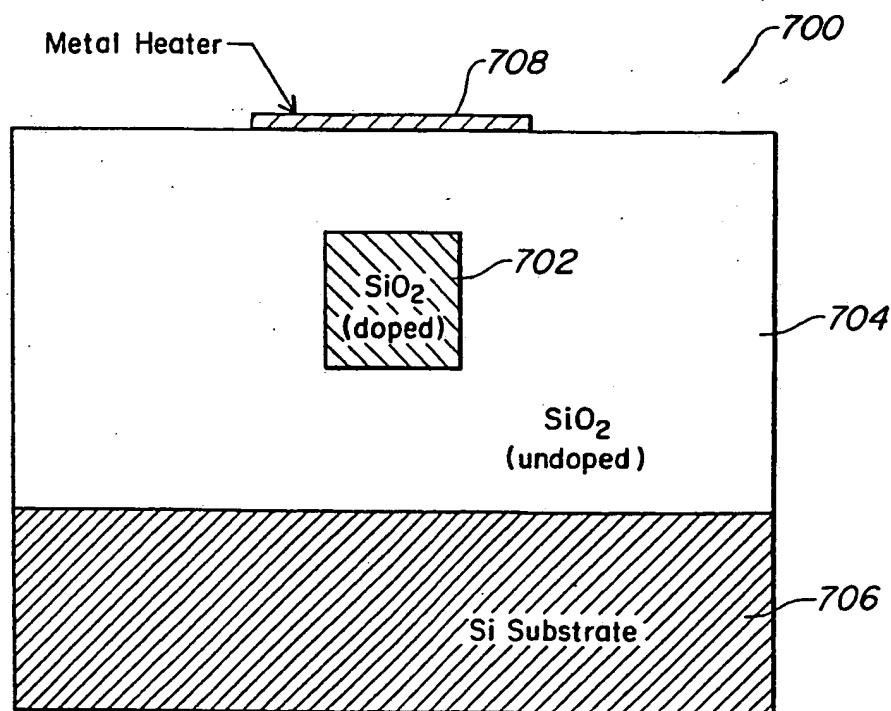
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*FIG. 2A**FIG. 2B**FIG. 2C*

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**FIG. 4****FIG. 5**

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*FIG. 6**FIG. 7*

# INTERNATIONAL SEARCH REPORT

Inter. Application No

PCT/US 00/29678

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 7 G02F1/01 G02F1/313

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 98 57207 A (MASSACHUSETTS INST TECHNOLOGY) 17 December 1998 (1998-12-17) abstract; claim 6; figures 10,27 page 13, line 36 -page 14, line 21 page 38, line 3 -page 39, line 18 & US 6 101 300 A (JOANNOPOULOS JOHN D ET AL) 8 August 2000 (2000-08-08) cited in the application -----	1,16

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

\* Special categories of cited documents:

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Date of the actual completion of the international search

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European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax (+31-70) 340-3016

Authorized officer

Iasevoli, R

# INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter. Application No

PCT/US 00/29678

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9857207 A	17-12-1998	US 6130969 A	10-10-2000
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